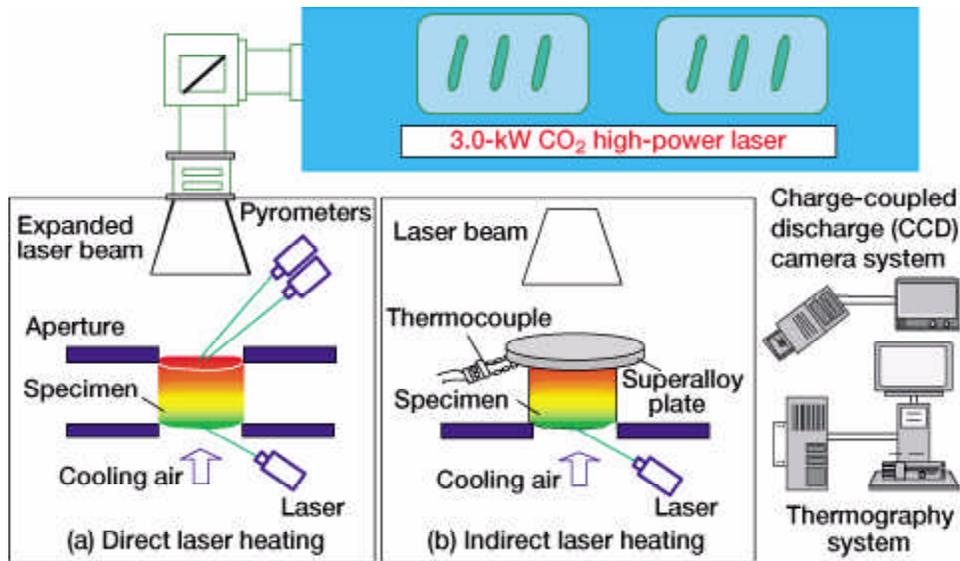


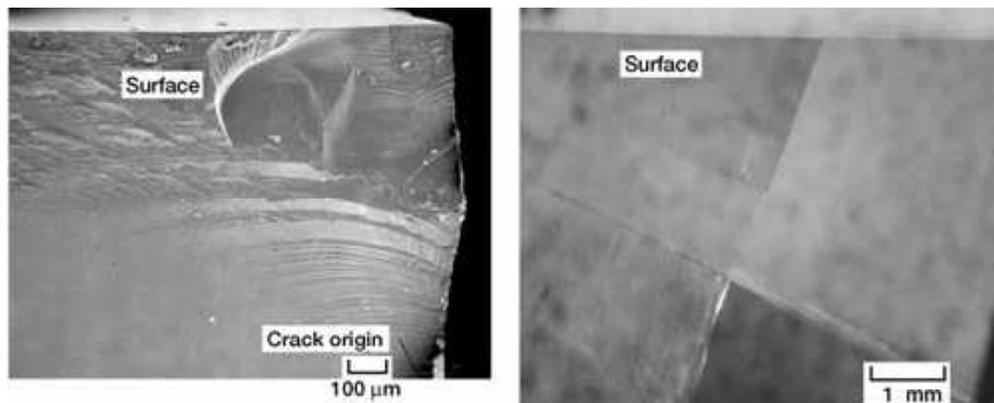
Thermal Mechanical Stability of Single-Crystal-Oxide Refractive Concentrators Evaluated for High-Temperature Solar-Thermal Propulsion

Recently, refractive secondary solar concentrator systems were developed for solar thermal power and propulsion (ref. 1). Single-crystal oxides-such as yttria-stabilized zirconia ($Y_2O_3-ZrO_2$), yttrium aluminum garnet ($Y_3Al_5O_{12}$, or YAG), magnesium oxide (MgO), and sapphire (Al_2O_3)-are candidate refractive secondary concentrator materials. However, the refractive concentrator system will experience high-temperature thermal cycling in the solar thermal engine during the sun/shade transition of a space mission. The thermal mechanical reliability of these components in severe thermal environments is of great concern. Simulated mission tests are important for evaluating these candidate oxide materials under a variety of transient and steady-state heat flux conditions. In this research at the NASA Lewis Research Center, a controlled heat flux test approach was developed for investigating the thermal mechanical stability of the candidate oxide. This approach used a 3.0-kW continuous-wave (wavelength, $10.6\ \mu\text{m}$) carbon dioxide (CO_2) laser (ref. 2). The CO_2 laser is especially well-suited for single-crystal thermal shock tests because it can directly deliver well-characterized heat energy to the oxide surfaces. Since the oxides are opaque at the $10.6\text{-}\mu\text{m}$ wavelength of the laser beam, the light energy is absorbed at the surfaces rather than transmitting into the crystals, and thus generates the required temperature gradients within the specimens. The following figure is a schematic diagram of the test rig.



High-temperature thermal gradient testing of single-crystal-oxide refractive solar concentrator using a high-power laser.

The thermal stress fracture behavior and failure mechanisms of these oxide materials were investigated, and the critical temperature gradients and corresponding absorbed power densities imposed on the crystals to cause failure were determined under various temperature and heating conditions. Steady-state thermal gradient tests were conducted on thin-disk specimens of $Y_2O_3-ZrO_2$, YAG, MgO, and Al_2O_3 (diameter, 25.4 mm; thickness, 1 mm) to determine the critical temperature differences across the specimen thickness that will initiate cracking. The laser power was continuously increased at a slow rate to heat the specimen under near steady-state conditions and to increase the temperature gradient across the specimen thickness with the heating time. Because the disk specimen broke off as soon as the material began to crack, the onset of cracking and the fracture of the specimen were recorded as a sudden temperature drop in the pyrometer temperature reading. The average critical temperature differences at failure were 81 ± 20 °C, 88 ± 21 °C, and 200 ± 35 °C for $Y_2O_3-ZrO_2$, YAG, and Al_2O_3 , respectively. Because the thermal gradients established in the secondary solar concentrator systems are due to the heat receiver cavity heating/cooling cycles and to a small portion of solar light energy being absorbed in the crystal components, the information obtained from this experiment can be of great importance in component design. The crack origins were typically observed near the back edges of the specimen because of a tensile stress state near the backside, as shown in the photomicrograph on the left ($Y_2O_3-ZrO_2$).



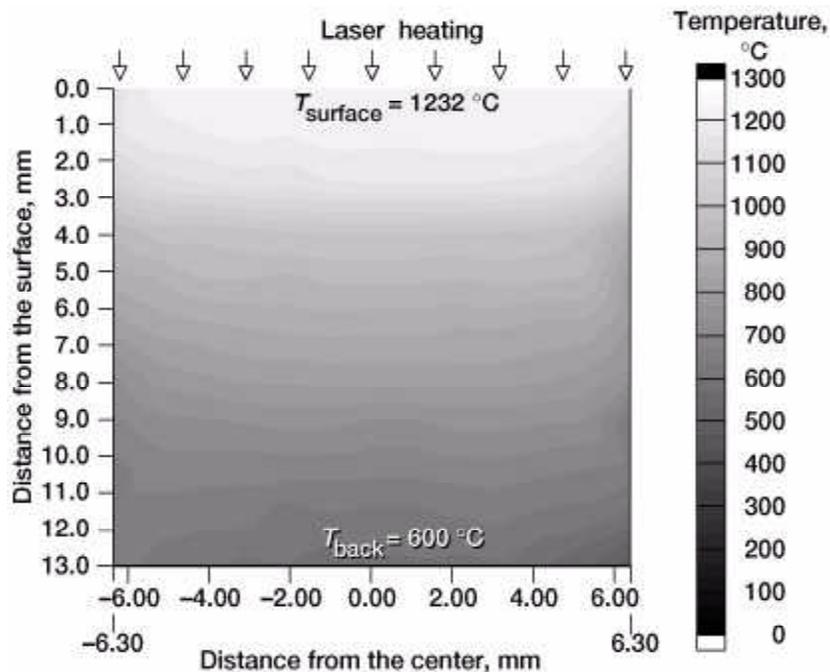
Crack and fracture morphologies of single-crystal oxides after laser testing. Left: SEM fractograph of the Y_2O_3 -doped ZrO_2 disk specimen after laser steady-state thermal gradient testing. Right: Surface shear-stress-initiated cleavage along the (110) plane in MgO after laser thermal transient testing (optical microscopy).

Laser transient thermal shock tests were conducted on single-crystal cylindrical specimens (diameter, 12.7 mm; length, 12.7 mm) with a total heating time of 60 sec and a subsequently increased laser power. During the test, heating/cooling profiles and temperature distributions were experimentally measured with thermography and pyrometry. Results were compared with analytical solutions and one-dimensional finite difference models. The critical power densities for crystal failure were approximately 15.3 W/cm², 56.9 W/cm², 39.1 W/cm², and 109.4 W/cm² for $Y_2O_3-ZrO_2$, YAG, MgO, and Al_2O_3 (sapphire), respectively. In the materials with low thermal conductivity and high thermal expansion, $Y_2O_3-ZrO_2$ and MgO, high compressive stresses and/or compressive

stress-induced (resolved) shear stresses initiated the surface cracks. On the other hand, in the materials with high thermal conductivity and low thermal expansion, Al_2O_3 and YAG, the cracks were more likely initiated deep in the crystals.

The photomicrograph on the right illustrates the surface shear-stress-initiated cleavage along the (110) plane in MgO. The modeled transient thermal stress distributions indicate that the surface compressive stresses and subsurface tensile stresses are responsible for the crystal failures observed under the laser transient heating conditions.

Single-crystal cylindrical specimens were also tested under a thermal gradient to simulate the heating/cooling cycles of a space mission. A typical thermography temperature distribution in a YAG specimen during the testing is illustrated in the final figure. Surface cracking was observed for the $\text{Y}_2\text{O}_3\text{-ZrO}_2$ and MgO specimens at a surface heating rate of approximately $15\text{ }^\circ\text{C}/\text{min}$ at $1200\text{ }^\circ\text{C}$. The YAG and Al_2O_3 specimens did not crack under the test conditions. Al_2O_3 (sapphire) exhibited the best thermal shock resistance of all oxide materials tested. The good thermal shock resistance of sapphire is attributed to its high strength, high thermal conductivity, and low thermal expansion coefficient.



Thermography temperature distribution in a YAG specimen (diameter, 12.7 mm; length, 12.7 mm) during near-steady-state laser heating.

References

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